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ABSTRACT

This booklet is part of an American Astronomical Society curriculum project designed to provide teaching materials to teachers of secondary school chemistry, physics, and earth science. The material is presented in three parts: one section provides the fundamental content of extragalactic astronomy, another section discusses modern discoveries in detail, and the last section summarizes the earlier discussions within the structure of the Big Bang Theory of Evolution. Each of the three sections is followed by student exercises and activities, laboratory projects, and questions and answers. The glossary contains unfamiliar terms used in the text and a collection of teacher aids such as literature references and audiovisual materials. (MH)

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# Extragalactic Astronomy

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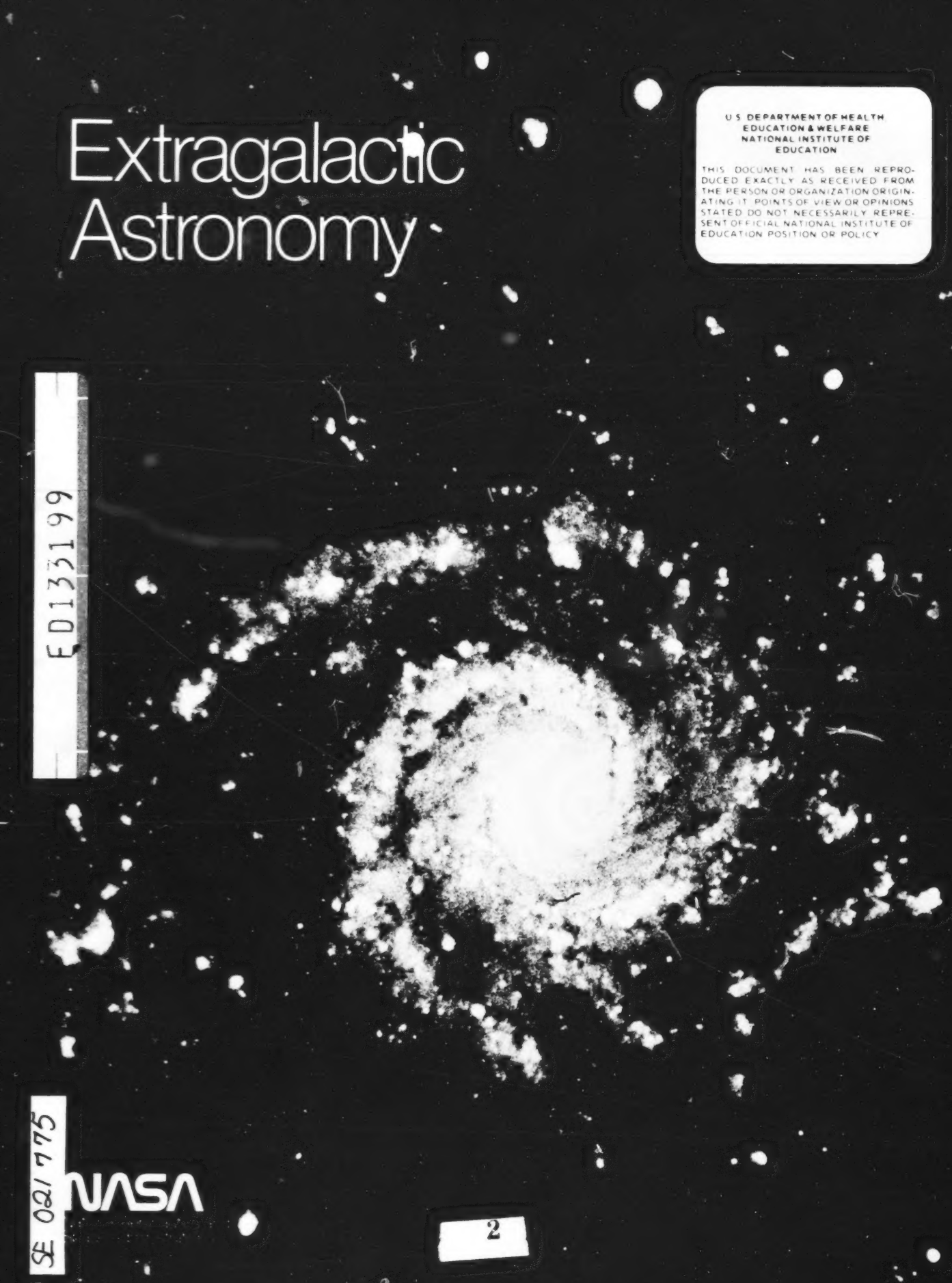

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# EXTRAGALACTIC ASTRONOMY:

## The Universe Beyond Our Galaxy

A curriculum project of the American Astronomical Society,

prepared with the cooperation of the

National Aeronautics and Space Administration and the National Science Foundation

by

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National Aeronautics and Space Administration
Washington, DC 20546 September 1976

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## PREFACE

In the past half century astronomers have provided mankind with a new view of the universe, with glimpses of the nature of infinity and eternity that beggar the imagination. Particularly, in the past decade, NASA's orbiting spacecraft as well as ground-based astronomy have brought to man's attention heavenly bodies, sources of energy, stellar and galactic phenomena, about the nature of which the world's scientists can only surmise.

Esoteric as these new discoveries may be, astronomers look to the anticipated Space Telescope to provide improved understanding of these phenomena as well as of the new secrets of the cosmos which they expect it to unveil. This instrument, which can observe objects up to 30 to 100 times fainter than those accessible to the most powerful Earth-based telescopes using similar techniques, will extend the use of various astronomical methods to much greater distances. It is not impossible that observations with this telescope will provide glimpses of some of the earliest galaxies which were formed, and there is a remoter possibility that it will tell us something about the edge of the universe.

The researches of the past 10 years, plus the possibility of even more fundamental discoveries in the next decade, are fascinating laymen and firing the imagination of youth. NASA's inquiries into public interest in the space program show that a major source of such interest is stellar and galactic astronomy. NASA's enabling Act, the Space Act of 1958, lists a primary purpose of NASA, "the expansion of human knowledge of phenomena in the atmosphere and space"; the Act requires of NASA that "it provide for the widest practicable and appropriate dissemination of information concerning its activities and the results of those activities."

In the light of the above, NASA is publishing for science teachers, particularly teachers of secondary school chemistry, physics, and Earth science, the following four booklets prepared by the American Astronomical Society (AAS) with the cooperation of NASA:

*The Supernova, A Stellar Spectacle*, by Dr. W. C. Straka, Department of Physics, Jackson State University, Jackson, Mississippi

*Extragalactic Astronomy, The Universe Beyond our Galaxy* by Dr. Kenneth C. Jacobs, Department of Astronomy, University of Virginia, Charlottesville, Virginia

*Chemistry Between the Stars*, by Dr. Richard H. Gammon, National Radio Astronomy Observatory, Charlottesville, Virginia

*Atoms In Astronomy*, by Dr. Paul A. Blanchard, Theoretical Studies Group, NASA Goddard Space Flight Center, Greenbelt, Maryland

The National Science Foundation has cooperated in this project by funding for the AAS a High School Astronomy Education Workshop in June 1974 at the University of Richmond in order to give the manuscripts a thorough pedagogic review in terms of curricular relevance and classroom use. The resulting publications provide exciting accounts of recent discoveries in the cosmos, and of the nature of the scientific thought and techniques by which scientists are trying to understand these discoveries.

NASA expresses its appreciation to the authors and to the members of the AAS Task Group on Education in Astronomy (TGEA), whose enthusiasm and energy carried the project to completion, particularly to Dr. Gerrit L. Verschuur, Director of the Fiske Planetarium, University of Colorado, who served as Director of the project; Dr. Donat G. Wentzel, Astronomy Program, University of Maryland, initiator of the project; Dr. Paul H. Knappenberger, Jr., Director, the Science Museum of Virginia and Chairman of the TGEA, who served as Workshop Director; and Herman M. Gurin, Executive Officer of the American Astronomical Society. To those who were enrolled in the Workshop and to others whose judgements and suggestions helped give the manuscripts the necessary scientific and curricular validity, NASA is grateful.

Appreciation is also expressed to the National Science Foundation for its support of the Workshop, to the University of Richmond for its cordial and efficient service as host to the Workshop, and to the NASA Goddard Space Flight Center for its assistance in making possible the publication of this project.

Technical Monitor for the project was Dr. Nancy W. Boggess, Staff Astronomer, Astrophysics Division, Office of Space Science, NASA. Coordinators of the project were Dr. Nancy G. Roman, Chief, Astronomy/Relativity, Office of Space Science, NASA, and Dr. Frederick B. Tuttle, Director, Educational Programs Division, Office of Public Affairs, NASA. Assisting until his retirement in June 1974, was Mr. Myrl H. Ahrendt, Instructional Materials Officer, Educational Programs Division.

September 1976

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## CONTENTS


| | | Page |
|---|---|---|
| I. | INTRODUCTION | 1 |
| II. | FUNDAMENTALS OF EXTRA GALACTIC ASTRONOMY | 3 |
| | A. The Milky Way Galaxy | 3 |
| | B. The Nebulae Are Galaxies | 4 |
| | C. Classifying Galaxies | 6 |
| | D. Clusters of Galaxies in Space | 7 |
| | E. Hubble's Law of the Redshifts | 9 |
| | F. Modern Discoveries Summarized | 11 |
| | Basic Exercises for Students | 13 |
| III. | MODERN DISCOVERIES IN GREATER DEPTH | 15 |
| | A. Extragalactic Radio Sources | 15 |
| | B. Violent Activity in Galaxies | 16 |
| | C. The Quasars | 18 |
| | D. The Primeval Fireball? | 21 |
| | E. X-Ray Sources Beyond Our Galaxy | 21 |
| | F. Faster Than the Speed of Light? | 22 |
| | G. Galaxies With "Radio Tails" | 24 |
| | Advanced Exercises for Students | 24 |
| IV. | THE "CONVENTIONAL" STORY OF COSMOLOGY | 27 |
| | Final Exercises for Students | 28 |
| | GLOSSARY | 31 |
| | REFERENCES AND TEACHING AIDS | 35 |

I

## INTRODUCTION

We live on the third planet (of nine) orbiting our Sun in the solar system. The Sun is a rather ordinary star residing near the periphery of a gigantic system of 100 billion stars which we call our *Milky Way Galaxy*. Outside our Galaxy lies the rest of the universe, populated with multitudes of galaxies and other strange denizens; this is the arena with which the young field of *extragalactic astronomy* concerns itself.

This single-topic brochure is for high school teachers of "physical science." Using it, they may introduce their students to a vital area of modern astronomy. Our goal is to provide a sense of "what has been found out there" by extragalactic astronomers. The material is presented in three parts. Section II provides the fundamental content of extragalactic astronomy. In Section III, modern discoveries are delineated in greater detail, while Section IV summarizes the earlier discussions within the structure of the *Big-Bang Theory* of evolution. Each of the three sections is followed by Student Exercises (activities, laboratory projects, and questions-and-answers).

The unit closes with a Glossary which explains unfamiliar terms used in the text and a collection of Teacher Aids (literature references and audiovisual materials for utilization in further study).

Kenneth Charles James

II

# FUNDAMENTALS OF EXTRAGALACTIC ASTRONOMY

## A. The Milky Way Galaxy

Extragalactic astronomy is the study of everything outside our own Milky Way Galaxy. Before going beyond it, however, we should first prepare ourselves by understanding thoroughly our own Galaxy. It may surprise you to learn that it was not "discovered" until about 1930 A.D.

In a dark, clear, night sky, three items are always evident to the unaided human eye: (1) several unblinking *planets* of our solar system (and often our Moon, but never Neptune nor Pluto); (2) about 3000 **twinkling** *stars*; and (3) a dim, irregular band of light arching from horizon to horizon called the Milky Way. Around 425 B.C., the Greek philosopher Democritus conjectured that the Milky Way consisted of multitudes of faint stars so densely crowded together as to appear as a luminous band. It was not until 1609 A.D., however, that this guess was verified by the Italian, Galileo Galilei, using one of the earliest optical telescopes. His telescope revealed millions upon millions of stars surrounding our Sun, with the greatest concentration in the direction of the Milky Way.

In the centuries that followed, men speculated upon the physical nature of the Milky Way. Some astronomers even used telescopes to count the numbers of stars visible in different directions in the night sky. By 1922, it was believed that our Sun resided at the center of a tremendous, flattened (disk-like) system of stars which appeared on the sky as the band of the Milky Way. Some scientists even believed that this star system filled the entire universe!

Soon thereafter, however, this conception of the Milky Way Galaxy was shown to be erroneous; the Sun is not at the center of the Galaxy, and the Galaxy does not fill all space. Already in 1917 it had been demonstrated that *globular clusters* (each a dense cluster of about 500 000 stars) are scattered throughout a spherical volume, with the Sun near one edge and the center of the Galaxy about 30 000 light-years distant toward the constellation Sagittarius. (One light-year is the distance traveled by a light ray in one year at a speed of 300 000 km per second – about 10 trillion km.) In 1927, studies of the motions of bright stars indicated that our Galaxy of stars rotates about the same center in Sagittarius. And, in 1930, it was further determined that *interstellar dust* pervades the galactic plane, obscuring distant stars and parts of the Milky Way such that the galactic center is hidden from view and the erroneous impression is created that the Earth lies at the center of the star system.

While the detailed structure of our Galaxy continues to be deciphered today (especially at *radio wavelengths*), it is possible to present a general picture, as shown in figure 1. About 100 globular clusters (G) are in the *halo* (H) spanning 100 000 light-years. Most of the 100 billion stars of the Galaxy define the rotating galactic *disk* (D) and the bulge (B), with the dense stellar *nucleus* (N) at the galactic center. Bright, young stars are found in the *spiral arms* (SA) in the central plane of the disk, and our Sun (⊙) lies 30 000 light-years from the center near a spiral arm.

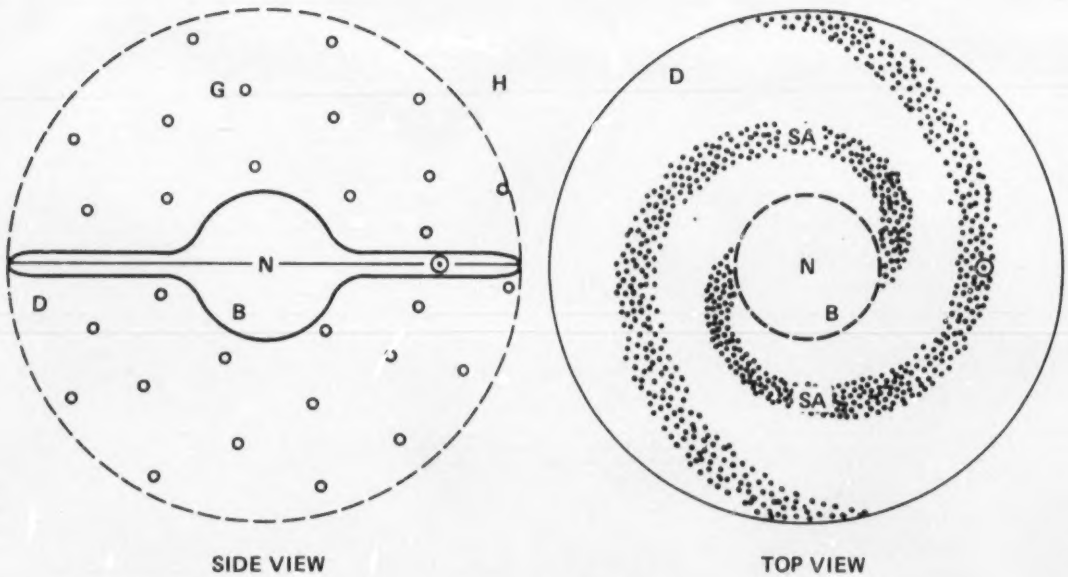



Figure 1

An analogy will assist us in understanding the extent of our Galaxy. Imagine that the Sun is reduced to the size of a basketball. On this scale, the Earth is a BB pellet 30 meters from the basketball, and the solar system has a diameter of 3 km. The nearest star is another basketball 8000 km away. Finally, imagine 100 billion basketballs scattered at similar separations in a disk 200 million km across, and you have a model of our Galaxy reduced in scale by 5 billion times!

### B. The Nebulae Are Galaxies

The universe outside our Milky Way Galaxy is populated by many billions of galaxies. Each galaxy is a well defined system of billions of stars, held together (like our Galaxy) by the attractive gravitational forces of all the component stars. The typical distance separating neighboring, large galaxies is about 3 million light-years, so that today we "see" these galaxies by light which actually left them millions of years ago. To visualize the rather crowded distribution of galaxies in space, consider this: large galaxies are spaced by about 30 times their own diameters, so a useful scale model is to imagine billions of dinner plates strewn 10 meters apart in all three dimensions. The mind-boggling picture, showing our enormous Galaxy to be but one of many similar systems, became clear only after December 30, 1924. On that date (which many consider the birthdate of modern extragalactic astronomy), the American astronomer, Edwin P. Hubble, announced the first proof that the *nebulae* are actually other galaxies beyond the confines of our Galaxy. Let us recount the story of the events leading to Hubble's discovery.

To describe a dim, fuzzy patch of light in the night sky, astronomers use the word *nebula* (Latin for "cloud"; the plural is nebulae). As early as 127 B.C., the Greek astronomer, Hipparchus, recorded a few naked-eye observations of nebulae among the "fixed stars." With the invention of the optical telescope (1600 A.D.), large numbers of nebulae began to be discovered and cataloged. By 1755, so many had been found that the German philosopher, Immanuel Kant, boldly speculated that they were "island universes" (like our own Galaxy) scattered throughout infinite space. (That Kant's guess was essentially correct was not known for almost 200 years!)

Then came the well-known catalogs of the nebulae. To simplify his search for *comets*, the Frenchman, Charles Messier, in 1781 published a list of 103 "Messier objects" (for example, the nearby *Andromeda galaxy* is called M31). Thereafter, the lists of nebulae grew rapidly, and, in 1864, the *General Catalogue of Nebulae* appeared, containing 5079 objects. Another famous list, the *New General Catalogue*, tabulated 7840 nebulae in 1888 (in it, M31 is denoted as NGC 224). By 1908, more than 15 000 nebulae appeared in the *Index Catalogues* (in which a typical nebula is designated, for example, as IC 310).

By the 20th century, large optical telescopes had revealed that some of the nebulae are *star clusters* (including globular clusters) in our Galaxy. The science of *spectroscopy* showed a few to be clouds of glowing gas within the Galaxy. (Spectroscopy first developed in the 19th century. It consists of (1) separating the light from an object into its component colors; (2) noting the relative intensities of the different colors; and (3) deciphering the intensity pattern in terms of the physical properties of the light-emitting object.) However, the nature of most of the nebulae remained unknown and as mysterious as ever.

The breakthrough came slowly. From the last decades of the 19th century, *novae* (plural of the Latin word *nova* meaning "new star") were observed in some of the mysterious nebulae. Since several of these "exploding" stars are seen each year in our Galaxy, it was argued that the nebulae are star systems like our Galaxy. By 1918, the great 152-cm and 254-cm optical telescopes had been erected on Mount Wilson in California, and Edwin P. Hubble used them to take high-resolution photographs of the nebulae M31 and M33 – photographs which proved these nebulae to be immense star systems. The puzzle, however, still lacked one piece – *the distances to the nebulae*; it was a question of whether the nebulae lie within our Galaxy or far beyond it. Hubble resolved the problem in 1924 by photographically identifying *Cepheid variable stars* (see below) in M31 and showing that the galaxy in Andromeda resides millions of light-years beyond our Galaxy. In addition, between 1924 and 1936, Hubble used the 154-cm telescope to count the numbers of nebulae in different parts of the sky. The nebulae occurred everywhere *except along the band of the Milky Way*, as would be expected for distant galaxies beyond the dusty obscurity of our galactic disk. He termed this area *"the zone of avoidance."*

A Cepheid variable star is a very bright, giant star which rhythmically pulsates in both size and brightness. The name derives from the first of its type found – Delta Cephei. The brightness variations are cyclic, with the pattern repeating itself in a time called the *period*. While the period may have any value from a few days to about 100 days, each Cepheid has a well-defined period and average brightness. Henrietta Leavitt at the Harvard College Observatory studied the Cepheids in the *Small Magellanic Cloud* (a small satellite galaxy

only 150 000 light-years from our Galaxy), and, in 1912, she discovered the *Period-Luminosity* law: "The longer the pulsation period of a Cepheid variable, the greater is its average (intrinsic) brightness." The absolute brightness scale was then calibrated by observing nearby Cepheids in our own Galaxy.

The nebulae became "galaxies" in 1924 when Hubble found Cepheids in M31. He measured the fluctuation in their periods of brightness and their average *apparent* brightnesses. (The Period-Luminosity law told him their average *absolute* brightnesses.) Recalling that a light source appears dimmer as the inverse square of its distance away, Hubble finally deduced the distance to M31 (millions of light-years – far beyond our Galaxy) by comparing the apparent and absolute brightnesses of the Cepheids in M31.

### C. Classifying Galaxies

Just as every snowflake (or fingerprint) is unique, no two galaxies are identical in form. However, by the beginning of the 20th century, several broad types of galaxy structures were recognized such that it became useful to classify them according to a simple scheme. Hence, a classification scheme – known as the *Tuning Fork Diagram* – (fig. 2), was developed by Edwin Hubble in 1925 using photographs taken at the largest optical telescopes.

At the left of the figure are *elliptical galaxies* which appear on the sky as smoothly luminous ovals (that is, ellipses); we assign them the letter E, followed by a number which increases from 0 to 7 as the form appears more and more elongated. (Ellipticals range from

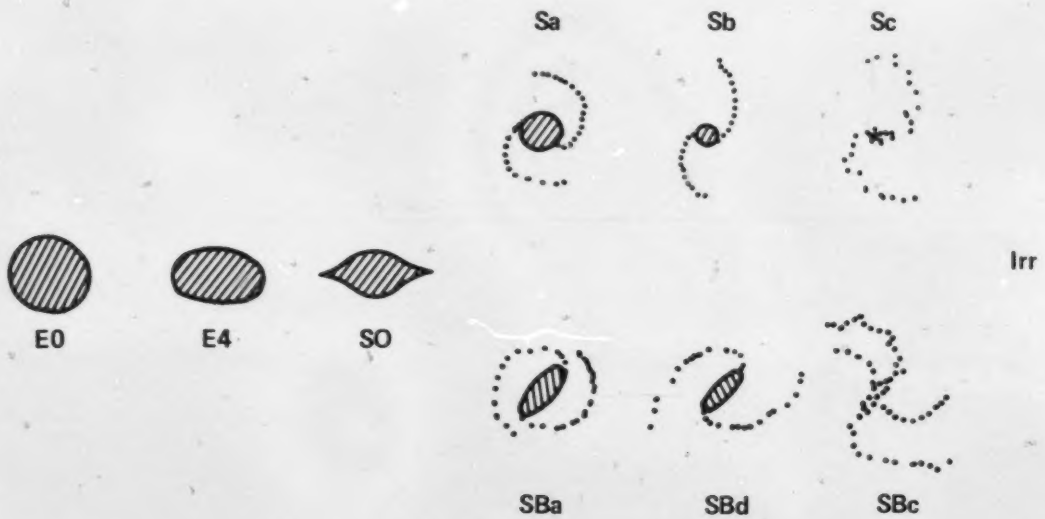



Figure 2

*giants* with 10 trillion stars to *dwarfs* with only 1 billion. Proceeding toward the right, we find the *lenticulars*, or *SO galaxies*, which look like very flat ellipticals with pointed edges (or, perhaps, spirals seen edge-on). The next broad class is the *spiral galaxies*; they appear as giant pinwheels of light, usually with a luminous *central region* and *spiral arms* trailing away to both sides of the center. Normal spirals are designated by the Letter S, followed by a, b, or c as the central region becomes less conspicious with respect to the arms. (Our Galaxy is believed to be an Sb spiral galaxy; see fig. 1.) If the central region appears as an elongated *bar* of light, we call the galaxy a *barred spiral*; here the symbol used is SB, followed by a, b, or c as the arms become less circular and more patchy. (A spiral galaxy is a very flat star system so that its visual appearance changes drastically when we rotate it from a face-on view, seen from above, to an edge-on view, seen from the side.) Finally, on the far right are the *irregulars* (with the symbol Irr); these consist of galaxies which appear too chaotic to be included in any of the preceding categories. (We will learn subsequently in this publication that unusual and violent events are taking place in some galaxies. When a galaxy shows visible signs of such peculiarities as optical jets, a super-bright nucleus, luminous "tail," evidence of an explosion, etc., it is termed *peculiar* and given the symbol Pec.)

It is a common mistake to regard the Hubble Tuning Fork Diagram (fig. 2) as an "age progression" or "evolutionary sequence." Some renowned astronomers have suggested that galaxies age and evolve through the sequence E → SO → S → Irr, while others have proposed just the opposite ordering. Today, we are only certain that *we do not know*; hence, the safest path for the reader is to regard figure 2 only as a "memory aid."

Figure 3 presents a montage of four photographs of typical galaxies. It should assist you in recognizing the different classes of galaxies. Photograph A (Yerkes Observatory, upper left) is the E5 elliptical galaxy NGC 4621, which is also a Messier object (M59). Photograph B (Hale Observatories, upper right) contains an edge-on view of the Sb (?) spiral NGC 891; C (Hale Observatories, lower left), a face-on view of the Sc spiral NGC 628 (M74); and D (Hale Observatories, lower right), the SBb barred spiral NGC 1300.

### D. Clusters of Galaxies in Space

Already in the latter half of the 19th century, it was known that the nebulae outside the band of the Milky Way appeared clumped on the sky. Today, we recognize that *galaxies are not uniformly scattered in space*; instead they tend to reside in *groups* and huge *clusters*, some containing as many as 10 000 member galaxies. The term, *field galaxy*, is used to describe a galaxy which does *not* seem to belong to any recognizable cluster.

Since the *average* separation between galaxies in the universe is 3 million light-years, the galaxies in a cluster must be more densely packed together – with spacings of only about 500 000 light-years (or even less). In our "dinner-plate model," the crowded situation in a cluster of galaxies may be represented by a three-dimensional grouping of dinner-plates scattered 2 m apart.

Our Galaxy belongs to a small group of about 20 galaxies called the *Local Group*. Most of the members are dwarf galaxies, with the three dominant giant spiral members: (1) our Galaxy, (2) the Sb Andromeda galaxy (NGC 224 or M31, about 2.2 million light-years distant), and (3) the Sc spiral (NGC 598 = M33 in the constellation Triangulum and slightly

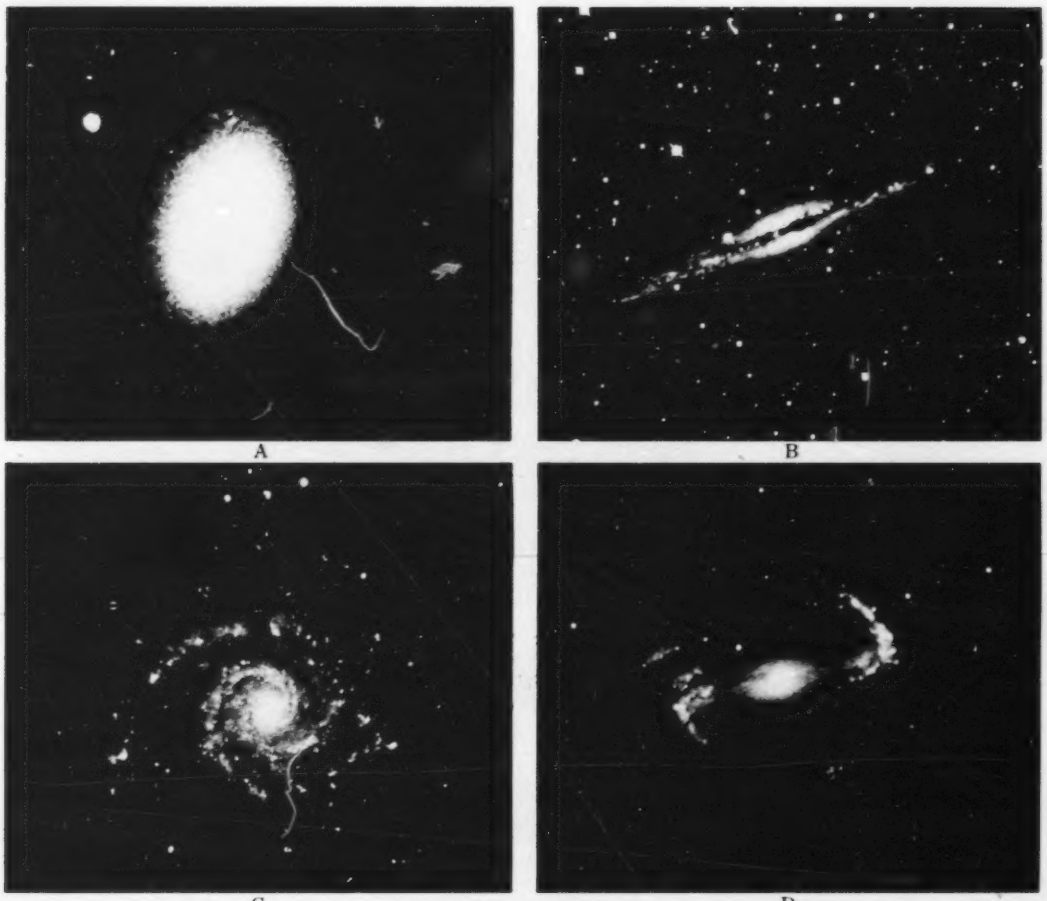



Figure 3

smaller than the Sb Andromeda galaxy). The nearest large cluster of galaxies is the 1000-member Virgo Cluster (in the constellation Virgo, about 40 million light-years away). Other well-known rich clusters are Coma, Corona Borealis, and the Hercules Cluster whose center is shown in figure 4 (Hale Observatories, 508-cm telescope photograph).

It has recently been conjectured that clusters of galaxies may aggregate into tremendous *superclusters* – that is, clusters of clusters. This idea is still unproven; indeed, the clusters appear to be *uniformly* scattered on the sky. On the other hand, the most recent results seem to indicate *clustering on every scale*, from two-galaxy associations to the entire universe of galaxies! We still await the final verdict.

Figure 4

### E. Hubble's Law of the Redshifts

To this point, the reader will have perceived the entire universe of galaxies as vast in size and content, but rather static. This picture of a motionless universe was shattered in 1929 when Edwin Hubble announced his *Law of the Redshifts*: "The dimmer a standard galaxy appears, the greater is its redshift." The simplest consistent interpretation of Hubble's law leads us to the statement: "All galaxies are moving away from our Galaxy at speeds which are directly proportional to their distances from us." Thus, we live in an expanding universe of galaxies!

Hubble's remarkable discovery merits closer scrutiny, for, in understanding it, we achieve important insight into the arena of modern extragalactic astronomy. These three fundamental theories underlie Hubble's law: (1) the *redshift*, (2) the *Doppler Effect*, and (3) standard-candle distances.

We see objects by the light which comes to us from them. Light of a given color may be thought of as a wave-like disturbance of electric and magnetic fields traveling through a

vacuum at the speed of light ($c$ = 300 000 km per s). The color is equivalent to the wavelength, $\lambda$, which is the distance between successive "crests" of the wave. In general, the light emitted with wavelength $\lambda_{em}$ by a luminous body (such as a galaxy) will be *observed* on Earth to have the different wavelength, $\lambda_{ob}$, upon arrival. When $\lambda_{ob}$ is *greater than* $\lambda_{em}$, the observer regards the light to be redder than was emitted, and he defines the *redshift*, $z$, as:

$$z = (\lambda_{ob} - \lambda_{em})/\lambda_{em}$$

When $\lambda_{ob}$ is *less than* $\lambda_{em}$, we say that the light is *blueshifted*. The redshift and blueshift are zero when $\lambda_{ob} = \lambda_{em}$.

At first glance, it would seem difficult to shift the color (wavelength) of light. However, in 1842, the Austrian mathematician, Christian Doppler, noted that wavelengths are altered when a wave source and an observer are in *relative motion* along the line joining them. Today, we call this the *Doppler Effect*. When a light source *recedes* from the observer at the speed $v$, the light waves appear "stretched out" to the observer, and the light is Doppler redshifted by the amount:

$$z = v/c$$

(This formula is accurate only when $v$ is *much smaller* than $c$.) For example, spectroscopic studies of the light from a nearby star might indicate $z$ = 0.001; we then say – based upon the Doppler interpretation of this redshift – that the star is moving away from us at 1/1000th the speed of light, or 300 km per s.

The third ingredient in Hubble's law is the *extragalactic distance scale*. How can one accurately and convincingly determine distances of millions and billions of light-years? Extragalactic astronomers utilize *standard-candle distances* which – disregarding the practical complexities and uncertainties involved – are conceptually rather simple. Suppose that all Sb galaxies have the *same intrinsic brightness* – that is, they are "standard candles" (like 100-watt light bulbs). Then, the dimmer an Sb galaxy appears on the sky, the farther away it is. In fact, *the apparent brightness is inversely proportional to the square of the distance*. Once we have calibrated the actual distance to one Sb galaxy (as Hubble did for the Andromeda galaxy using Cepheid variables, as shown above), the distance to every other recognizable Sb galaxy follows immediately from its relative apparent brightness. (For example, an Sb which appears *nine* times dimmer than M31 would be *three* times more distant, or a distance of 6.6 million light-years.) We can now appreciate the historical development of Hubble's law.

Between 1912 and 1925, spectroscopic studies at the Lowell Observatory revealed 40 nearby galaxies whose light exhibited redshifts; these could be interpreted as motions away from us. Hubble observed these galaxies, compared the apparent brightnesses of their brightest observable stars, and deduced distances to them. By 1929, he had shown that the redshifts were proportional to the distances, announced his Law of the Redshifts, and proclaimed the concept of the expanding universe. The measurements were then pushed to ever greater distances (where individual stars could not be seen and entire galaxies became standard candles), so that, by 1936, Hubble's law had been verified out to a distance of one-half billion light-years. Further progress had to await the completion of the 508-cm

optical telescope at Mount Palomar in California, and the redshift program resumed in 1951. Today, we know that Hubble's law holds to the largest galactic redshift measured, $z = 0.461$ (for the *radio galaxy* 3C 295, see Subsection III.A., below), corresponding to recession at about half the speed of light at a distance of approximately 6 billion light-years.

A useful computational formulation of Hubble's law may be written as:

$$v = Hd$$

where $v$ is the recessional speed (km per s) and $d$ is the distance (million light-years) of a galaxy. The symbol relating them is the famous *Hubble constant*, $H$, which has the value: $H = 20$ (km per s) per (million light-years). For example, a galaxy at the distance of the center of the Virgo Cluster – $d = 40$ million light-years – is moving away from us at the speed $v = 20 \times 40 = 800$ km per s.

### F. Modern Discoveries Summarized

The first half of the 20th century saw the birth of extragalactic astronomy and the realization that its arena is the expanding universe of multitudes of clusters of galaxies. This was accomplished by observations of visible light arriving at the Earth's surface. The modern era of extragalactic astronomy may be dated from the end of World War II, when advanced technology opened new observing "windows" to the universe: (1) the *infrared* and *radio* windows through the Earth's atmosphere and (2) the *ultraviolet* and *X-ray* windows from spacecraft above the atmosphere.

The varieties of *electromagnetic radiation* should be clearly understood before we proceed. The wavelength, $\lambda$, of light was mentioned in Subsection II.E. *Visible* light is one example of electromagnetic radiation, with characteristic wavelengths in the range $\lambda$ = 4000 Å (blue) to 7000 Å (red). (Å is the abbreviation for *Ångström*, a unit of length equalling 1 100 000 000th cm. There are 20 000 wavelengths of green light in one cm.) *Longer* wavelengths or electromagnetic radiation are termed: (1) *infrared* for $\lambda$ = 7000 Å to 0.01 cm, and (2) *radio* (or *microwave*) for longer than 0.01 cm. *Shorter* wavelengths correspond to: (1) *ultraviolet* for $\lambda$ = 100 Å to 4000 Å, (2) *X-ray* for $\lambda$ = 1 Å to 100 Å, and (3) *gamma ray* for $\lambda$ shorter than 1 Å. Astronomical observations from the surface of the Earth are severely limited by our atmosphere which is opaque to all electromagnetic radiations except visible light, some infrared ($\lambda$ = 7000 Å to 0.001 cm), and radio waves ($\lambda$ = 0.1 cm to about 50 m).

With new tools and "windows" available, the way was paved for several significant discoveries during the last quarter century. Let us briefly discuss the following: (1) extragalactic radio sources, (2) exploding galaxies, (3) the quasars, (4) cosmic microwave background radiation, and (5) extragalactic X-ray sources.

The American, Karl G. Jansky, opened our "radio window" on the universe in 1931-2 when he detected radio waves coming to the Earth from the Milky Way. He did this with a large antenna and very sensitive radio receiver – a sophisticated version of your own home radio set. Large radio telescopes were constructed after World War II, and, in 1946, the first extragalactic radio source was discovered – Cygnus A in the constellation Cygnus. A *radio source* is a localized region of the sky from which radio waves are observed to come. By the

late 1950's, many such radio sources were known, and some were found to be caused by giant elliptical galaxies – the so-called radio galaxies. In the 1960's, others were associated with exploding galaxies and quasars (see below). (Radio sources are considered further in Subsection III.A.)

From our presentation so far, you might think that all galaxies are majestic star systems, with some gas and dust in them, quietly pursuing their existences in space. Indeed, most astronomers thought the same until quite recently. In 1943, however, Carl K. Seyfert (pronounced "see-furt") discovered some spiral galaxies – the *Seyfert galaxies* – with small, bright nuclei (centers) from which gas clouds stream at expansion speeds around 1000 km per s. Additional evidence for galactic "violence" came in 1961, when the irregular galaxy M82 was telescopically photographed and its core was found to have undergone a titanic explosion a million years ago! The enormous energy output of the numerous radio galaxies and quasars (see below) also attests to the fact that "activity" and "violence" characterize our universe. (For additional details, see Subsection III.B.)

Perhaps the strangest discovery was that of the *quasi-stellar objects* (popularly termed *quasars*; pronounced "kway-zars") in the early 1960's. On photographs taken at telescopes quasars look like stars, but their light is incredibly redshifted. Hence, if they abide by Hubble's law, quasars must be billions of light-years distant and much brighter than the brightest known galaxy. Moreover, many of them *fluctuate in brightness* with time-scales less than a year, so that their intrinsic *size is less than a light-year* (as shown in Subsection III.C.). Quasars are the most controversial extragalactic objects in astronomy today, but many astronomers are beginning to believe that they may represent the overwhelmingly active nuclei of giant elliptical galaxies.

A less strange, but no less spectacular, observation occurred in 1965 when weak microwave radiation (at cm wavelengths) was detected and found to be impinging upon the Earth uniformly from all directions. Today, many careful observations later, it is generally agreed that this *cosmic microwave background radiation* is the feeble remnant of the primeval fireball, the fiery holocaust which marked the beginning of our universe. This is not surprising, based upon the observed expansion of the universe (Hubble's law). In the past, galaxies were closer together and the universe was denser, and, in the ultimate past, the beginning, the universe was so dense and hot as to be aptly called a "holocaust" or "fireball." (See Subsection III.D.)

Finally, we recall that X-rays cannot penetrate the Earth's atmosphere, so that X-ray astronomy is dependent upon spacecraft. *Extragalactic sources of X-radiation* were first detected in the early 1970's by orbiting NASA satellites. Such X-ray sources were soon determined to be of two kinds: (1) *point sources* associated with "energetic" objects such as radio galaxies, Seyfert galaxies, and quasars, and (2) *distributed sources* occurring in large, rich clusters of galaxies. The latter have diameters of several million light-years, and the X-radiation appears to come from extremely hot gas filling the clusters. It is not yet known whether this gas is heated by "erupting" galaxies in the clusters or simply "stirred up" by the orbital motions of the galaxies composing the clusters. (See Subsection III.E.)

We see then that the contents of our universe are complex both in terms of spatial structure and temporal evolution. Indeed, the universe itself is an active and dynamic entity.

## BASIC EXERCISES FOR STUDENTS

The *fundamentals* of extragalactic astronomy have been spelled out in Section II. The following class activities and exercises may be used by the teacher to augment and verify student grasp of the material.

**Class Activities:**

1. On a *dark, clear* night, locate and study the *Milky Way* with your eyes. Identify the center of our Galaxy in the constellation Sagittarius. (The Milky Way passes overhead in summer and winter. In northern latitudes, Sagittarius is visible only in June, near the southern horizon.)

2. In mid-winter, those in northern latitudes can visually find the Andromeda galaxy in the constellation Andromeda. Study this galaxy with a good pair of binoculars. If you live in the southern hemisphere, do the same for the *Magellanic Clouds*. (Prepare yourself beforehand by learning the configurations of the constellations near each object; consult, for example, *The Norton Star Atlas*.)

3. Refer to several astronomy texts to learn about the *Local Group* of the galaxies. Then, with cardboard or styrofoam, construct a three-dimensional model of the Local Group on a scale where 1 cm represents 10 000 light-years.

4. Do some outside reading on *spectroscopy*, and write a report on "The Astronomical Applications of Spectroscopy." (One or more students might also give presentations to the class on this important topic.)

5. Students can learn to *classify galaxies* with the aid of a small magnifying glass and Palomar Sky Survey photographs of the constellation Virgo (or even figure 4). Record the relative numbers of elliptical and spiral galaxies identified on each print. (You might borrow the prints, or purchase them from the Caltech Bookstore, Pasadena, California 91109. See "All-Weather Observing: Student Use of Palomar Sky Survey Prints" by Donat G. Wentzel in *Mercury*, No. 2, pp. 13, January/February 1973.)

6. Teach the students to graph linear equations, and, then, set them the task of graphing *Hubble's law* $v = Hd$, with suitably labelled axes.

7. Verify the "inverse square law" of brightness in a darkened room with a movable light bulb. From a fixed point, measure the distance to the light with a meter stick and the brightness with a light meter (such as is used in photography). The quantity (brightness) $\times$ (distance)$^2$ should remain constant for all positions of the light bulb.

8. Demonstrate the *Doppler Effect* with an automobile and a portable tape recorder. Record the sound of the auto horn as the car approaches and passes the tape recorder at several different speeds. Since shorter wavelengths sound higher-pitched in frequency, your students should be able to recognize the car approaching, passing, and receding – as well as its relative speed. Determine also if they can identify the horn "redshifted"? "blueshifted"?

**Questions With Answers:**

**Q1:** Why was extragalactic astronomy impossible before 1600 A.D.?

**A1:** Telescopes were not invented until then. The naked human eye can barely discern the Andromeda galaxy and the Magellanic Clouds, but *no other* extragalactic objects.

**Q2:** Is a *light-year* a year with only 364 days?

**A2:** No, it is the distance light travels in a vacuum in one year.

**Q3:** Describe the structure of the Andromeda galaxy.

**A3:** Simply consult figure 1, as the Sb Andromeda galaxy is very similar to our own Galaxy.

**Q4:** Where and what is the *"zone of avoidance?"*

**A4:** It is the band of the Milky Way on the sky. Galaxies seem to "avoid" this band, since the dust in our galactic plane obscures distant galaxies.

**Q5:** Who was the most famous extragalactic astronomer of the early 20th century – the "father of extragalactic astronomy"?

**A5:** Edwin P. Hubble.

**Q6:** Draw the *Hubble Tuning Fork Diagram* and name at least *five* different types of galaxies; do all of this from memory.

**A6:** See figure 2 and Subsection II.C. Some types are: giant ellipticals, dwarf ellipticals, lenticulars (SO), normal spirals, barred spirals, irregulars, and peculiars.

**Q7:** What practical impediment is there to carrying on two-way radio communications with intelligent beings living in the Andromeda galaxy?

**A7:** Each two-way conversation requires *4.4 million years* to complete!* (Also, there may be no intelligent beings residing in that galaxy!)

**Q8:** How would you recognize a *quasar*?

**A8:** It is star-like on a photograph and is enormously redshifted. Its apparent brightness might also vary within a year.

**Note:* Radio waves travel at the speed of light, and the Andromeda galaxy is a distance of 2.2 million light-years from our Galaxy.

## III

## MODERN DISCOVERIES IN GREATER DEPTH

In Subsection II.F., the exciting discoveries of modern extragalactic astronomy were introduced. However, to fully appreciate the fact that our universe is not merely empty space through which galaxies are quietly promenading in accordance with Hubble's law of cosmic expansion, the reader must be exposed to the details of these modern findings. This is the intent of Section III. The student will find that significantly more effort is required to understand this new material.

### A. Extragalactic Radio Sources

*Radio astronomy* is the study of our universe through the "radio window" of the atmosphere. This window permits extraterrestrial electromagnetic radiation in the wavelength range $\lambda$ = 0.1 cm to 50 m to reach the Earth's surface unimpeded. Because the radio signals are very weak, large metallic "dishes" (hundreds of m across) are used to collect and focus them (by reflection) upon exceedingly sensitive radio receivers. We call this combination a *radio telescope.*

The large aperture (diameter) is also necessary if the radio telescope is to achieve good *angular resolution* – that is, the ability to distinguish accurate direction and fine detail on the sky. (We did not say "night sky," since radio telescopes operate both day and night.) The wave-like nature of electromagnetic radiation places the following intrinsic limitation upon the angular resolution, $\theta$, of an electromagnetic detector of aperture $a$ when the radiation detected has wavelength $\lambda$:

$$\theta = 3500\ (\lambda/a)\ \text{arc-minutes}$$

(The Glossary explains the meaning of the units of angular measure: arc-degree, arc-minute, and arc-second.) The human eye is one such detector, with an angular resolution in visible light of 1 arc-minute (the apparent size of an apple 350 m distant; 1/30th the angular diameter of the Moon). To attain this same resolving power with a radio telescope operating at $\lambda$ = 10 cm, however, requires an aperture of 350 m!

In the decades since its humble beginning with Karl G. Jansky in 1931-2, radio astronomy has provided a wealth of knowledge concerning our Sun, the solar system, and the structure and content of our Galaxy. However, since this brochure addresses the more distant extragalactic realm, this subject matter is not included.

The first *extragalactic radio source* – Cygnus A – was discovered in 1946 as a localized region of radio emission in the constellation Cygnus. By the early 1950's, many such radio sources had been found using single radio telescopes. In 1953, the *Magellanic Clouds* (two small companion galaxies to our Galaxy 170 000 light-years distant) were identified as weak radio sources by scientists in Australia; soon thereafter the nearby *Andromeda galaxy* was "seen" at the wavelength $\lambda$ = 21 cm.

Further understanding depended critically upon the *identification of the optical counterpart* of each radio source. Single radio telescopes, however, provided radio source *positions* accurate to only several arc-minutes. Identification was sufficiently easy when a large angular-diameter object – such as M31 – occurred at the position of the radio source, but, in most cases, there were many optical candidates for each radio source. It was clearly necessary to increase the radio angular resolution, and the solution came in the form of the *radio interferometer*. In simple terms, this device mimicks a huge radio telescope by utilizing two (or more) widely separated "single-dish" radio telescopes joined together electrically. The effective aperture of the resulting instrument is the distance between the two radio telescopes so connected. Hence, an angular resolution (and positional accuracy) or 1 arc-second can be obtained for a separation of about 10 km.

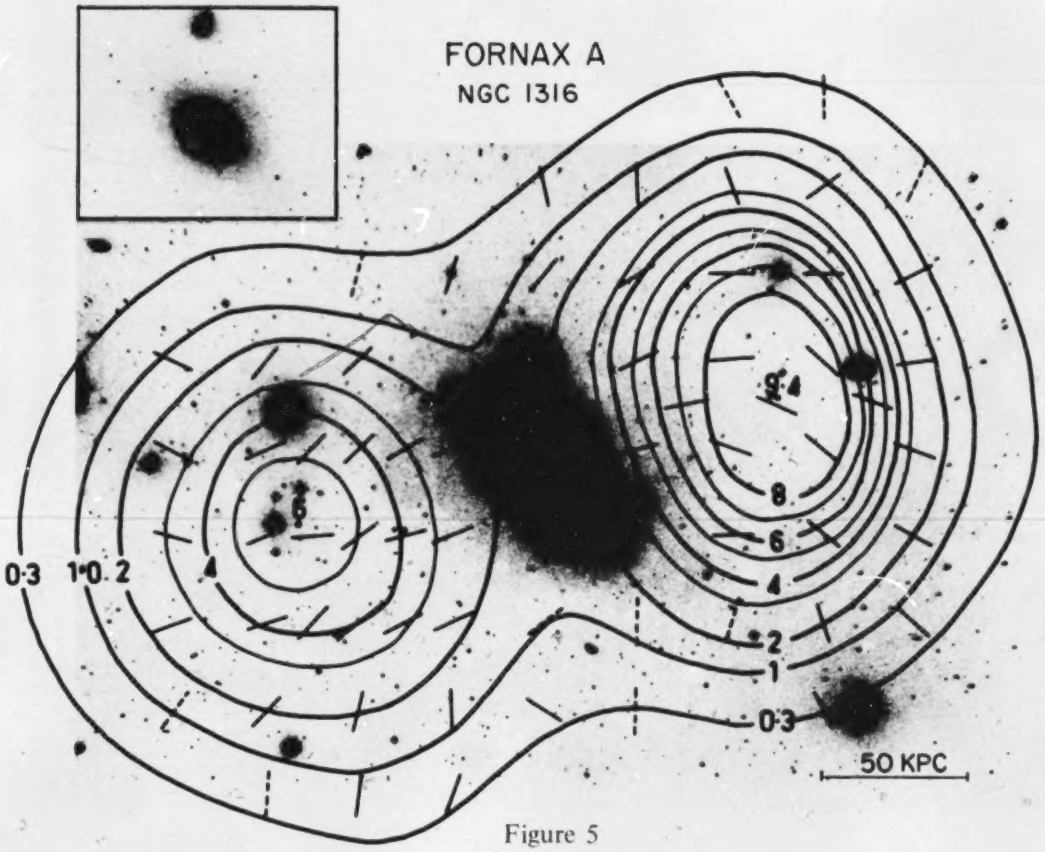
Using such radio interferometers during the 1950's, radio astronomers accumulated enormous catalogs of precisely positioned radio sources. (A good example is the *Third Cambridge* (England) *Catalogue*, wherein the 273rd source listed is designated 3C 273.) The optical identifications which followed produced staggering results. Most "ordinary" galaxies emit *some* radio radiation (like our own Galaxy), and, among large elliptical galaxies, about one in 100 000 is an ultra-powerful radio galaxy (see below). In addition, large numbers of weak (perhaps, very distant) radio sources were found to have *no* associated optical object. In the 1960's, many of the "exploding" galaxies and quasars were discovered to be strong radio sources (see the next two subsections).

Radio galaxies resemble giant elliptical galaxies optically, but the radio radiation associated with them is about 10 000 times stronger than the radio power of our Galaxy. Many exhibit a "bright core" of radio emission centered on the nucleus of the galaxy. In most cases, the radio sources are doubles – as illustrated in figure 5 below for Fornax A (Hale Observatories photograph) – with the bulk of the radiation coming from a region on either side of the optical galaxy and separated by about 300 000 light-years. It is currently thought that the nucleus of a radio galaxy is a region of extraordinary violence, which – in some unknown way – powers its radio sources for periods of around 100 000 years. Beyond this, we are only confident that the radio emission itself is synchrotron radiation, that is, radio waves emitted by electrons which are spiraling about in magnetic fields at relativistic speeds (essentially the speed of light $c$). Finally, the largest radio source known is the double source associated with the radio galaxy 3C 236, which, in late 1974, was found to span a separation of 19 million light-years.

### B. Violent Activity in Galaxies

Strong radio galaxies provided early indications that *galactic nuclei can be regions of violent activity*. Optical support for this idea was obtained from the giant elliptical galaxy M87 (NGC 4486), a strong radio source in the nearby Virgo cluster of galaxies. For example, a short-exposure, telescopic photograph revealed a luminous "jet" emerging from the nucleus of the galaxy (see Figure 7).

Such "nuclear violence" is not restricted to elliptical galaxies. Thirty years ago, Carl Seyfert discovered and classified a dozen *Seyfert galaxies* – spiral galaxies with bright, active, star-like nuclei. Spectroscopy (and the Doppler Effect) reveals that hot gas is expelled from Seyfert nuclei at speeds up to 1500 km per s; radio telescopes show many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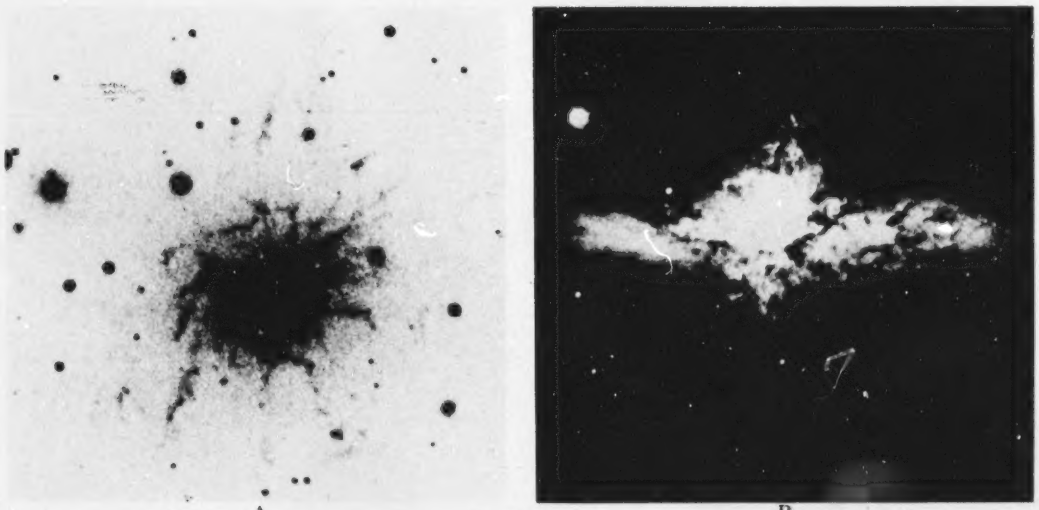

A B

Figure 6

It is even possible that our Galaxy is "violent." Radio observations of the galactic center disclose large clouds of hydrogen gas moving away from the nucleus at about 100 km per s. This would imply a rather "weak" explosion, but is also possible that the Galaxy is becoming a Seyfert.

### C. The Quasars

By 1960, extragalactic astronomers thought they basically understood the expanding universe of galaxies. Only the detailed mechanisms for producing active galactic nuclei and radio sources remained to be spelled out. However, in late 1960, the strong radio source 3C 48 was identified with a "star" on telescopic photographs. Since this appeared to be the first *radio star* ever discovered, its light was quickly analyzed spectroscopically. The result was completely *indecipherable* – nothing like it had ever been seen before! The object was designated a *quasi-stellar radio source* (abbreviated QSRS), since it looked "star-like." Later, the popularized term "*quasar*" became fashionable. A quasar with no detectable radio emission is called a *quasi-stellar object* (QSO).

Early in 1963, a second radio source, 3C 273, was found to be a quasar. But now, the American astronomer, Maarten Schmidt, uncovered a vital clue: the light emitted by 3C 273 was redshifted by $z = 0.16$. In the normal context of Hubble's law (Subsection II.E.), this object would be receding from us at 16 percent of the speed of light and would be 2 billion light-years distant. Astronomers might easily have accepted this finding but for one fact: the stellar image of 3C 273 appeared rather bright – at the cosmological distance implied by Hubble's law, this quasar would have to have been 100 times brighter than the brightest galaxy ever observed. In addition, an *optical "jet"* was emerging from 3C 273, as indicated in the (Hale Observatories) photograph shown as figure 7.

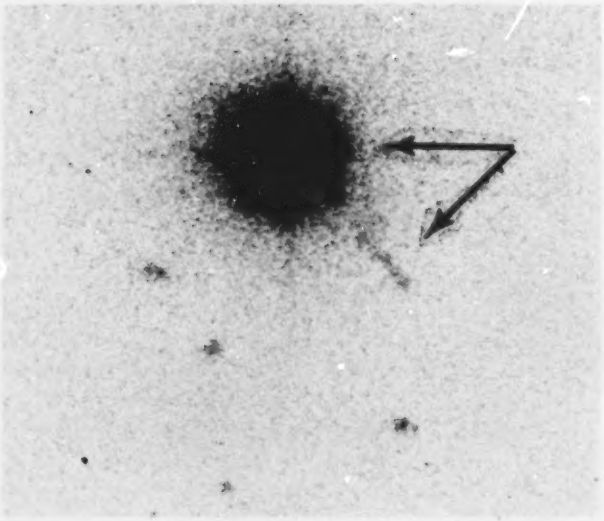

Figure 7

For awhile, 3C 273 simply was regarded as an extremely bright version of the radio galaxy M87. However, the quasar was readily identified on old photographs spanning several decades of time, and careful analysis soon disclosed that it *varied dramatically in optical brightness in less than 10 years*. This immediately implied that most of the light came from a region *smaller than 10 light-years* in diameter, since the far side of a larger object could not possibly coordinate its activity with the near side within 10 years (even at the speed of light). Now extragalactic astronomers face a tremendous dilemma . . . how can a violently fluctuating "object" only 10 light-years in size be emitting the light of 100 large galaxies?

Today, more than 1000 quasars are known, and redshifts have been measured for several hundred of them. We have good evidence of the existence of a quasar when a *star-like optical image* is associated with a *radio source*, but we are certain it is a quasar when the "star's" light is *highly redshifted*. If quasar redshifts indicate cosmological distances (via Hubble's law), quasars have the following charactersitics:

(1) They are brighter optically than the brightest galaxies.
(2) They are even stronger infrared emitters than Seyfert galaxies.
(3) As radio sources, they are indistinguishable from strong radio galaxies.
(4) They are ejecting hot gas at thousands of km per s.
(5) They can vary in brightness on time scales from years down to months. Hence, the "smallest" quasar emits the bulk of its radiation from a region only a *light-month* across (less than 100 times the size of the solar system).

Quasars tend to exhibit large redshifts, $z$. As of mid-1974, the largest redshift known was $z = 3.53$ for the quasar OQ 172 (in the constellation Boötes). For this object, light emitted in the far ultraviolet ($\lambda_{em} = 1500$Å) is observed on Earth as red light ($\lambda_{ob} =$

6800 Å). But the Doppler Effect formula of Subsection II.E. – ($z = v/c$) – is clearly inapplicable at such enormous redshifts, as it would imply that this quasar is receding from us *faster* than the speed of light – a physical impossibility. Whenever $z$ is not small compared to 1, it is necessary to use the relativistic Doppler formula:

$$v/c = (2z + z^2)/(2 + 2z + z^2)$$

We recover the old Doppler formula as $z$ becomes smaller, and in no case does $v$ ever exceed $c$. For example, the quasar OQ 172 is receding from our Galaxy at about 91 percent of the speed of light.

Our brief discussion has only touched on the principal properties of quasars. Evidently they are very strange and wondrous objects. In fact, since the discovery of the quasars, some astronomers have seriously questioned whether Hubble's law applies to them at all! Thus arose the redshift controversy of the past decade. Most extragalactic astronomers supported the "standard" interpretation: that the redshifts arise from recession speeds which imply *cosmological* distances. A vocal minority subscribed to "*nonstandard*" redshifts, which generally had the effect of making the quasars nearby "local" objects with unspectacular properties.

An early "nonstandard" suggestion was that quasars are compact, luminous objects ejected explosively from our Galaxy (or another nearby galaxy) at relativistic speeds. Another such school of thought maintained that quasars are physically associated with nearby, large, spiral galaxies. To others it appeared that (a) there seem to be too many quasars with redshifts very near $z = 1.95$, and (b) quasars appear randomly scattered on a plot of redshift versus apparent brightness – not at all in line with Hubble's law. Additional evidence came in late 1973, when two quasars near the radio source 4C 11.50 (in the constellation Serpens) were found with very different redshifts – $z = 0.436$ and $z = 1.90$ – but separated by only 5 arc-seconds on the sky.

The points raised by the "nonstandard school" were very valuable in stimulating the refined observations needed to show that *quasars fit consistently within the standard interpretation*. That is, the reader can now (reasonably) safely assume that quasars are at *cosmological distances*. As more and more quasars were observed, it became energetically unfeasible to eject them from ordinary galaxies, and the earlier apparent overabundance of quasars near $z = 1.95$ disappeared. Also, no blueshifted quasar has ever been seen; in 1973, the most promising candidate – the variable object BL Lacertae – was shown to be a redshifted quasar. Many of the "strange associations" are readily interpreted as mere coincidences in position on the sky. The year 1973 ended with the following four very strong indications of the correctness of the cosmological (standard) interpretation:

(1) Several quasars were observed in *clusters of galaxies*, with precisely the *same* redshift as the cluster galaxies.
(2) It became apparent that all quasars are *not* "standard candles." However, it was found that the *most luminous* quasars have the *same* intrinsic brightness and *do conform to Hubble's law.*
(3) Long-exposure photographs at the 508-cm Palomar telescope revealed intrinsically *weak* quasars to be the *very bright nuclei of giant elliptical galaxies.*

(4) Optically variable quasars were seen to look "star-like" *at their brightest*, but like bright spots at the centers of active galaxies *at their dimmest.*

By combining all of these clues, we now believe that *a quasar is simply the ultra-violent phase* (lasting about a million years) *of the nucleus of a massive galaxy* – the point at which that nucleus completely outshines the parent galaxy, ejects vast quantities of particles and gas, and creates strong radio sources (in many cases). That is, quasars are the brightest members of a class of objects such as radio galaxies and Seyferts. In none of these cases do we yet completely understand *how* the nucleus operates. Extragalactic astronomers of the future must untangle that mystery.

### D. The Primeval Fireball?

When matter is rapidly squeezed into a smaller volume, it gets hotter. If our universe is presently expanding in accordance with Hubble's law, it must have been smaller and denser in the past. Carrying this idea back about 12 billion years, we would find that the universe was so compressed and hot that it was dominated by a holocaust of intense radiation – the *primeval fireball* – much like the fireball of a hydrogen bomb. Decades ago, scientists predicted that from such a fiery beginning the universe would expand, the fireball radiation would cool, and, by today, the weak remanent radiation should be observed streaming toward the Earth from all sides.

Nevertheless, Arno A. Penzias and Robert W. Wilson of the Bell Telephone Laboratories, while studying weak radio static in 1965, were completely surprised when they accidentally discovered *microwave radiation* bombarding the Earth uniformly from all directions. By the end of the 1960's, this "cosmic microwave background radiation" was determined to be uniform in direction to better than 3 parts in 10 000, and its intensity had been measured at wavelengths from 1 mm to 21 cm.

Since observations at mm wavelengths were extremely difficult to carry out, high-altitude balloons and rockets were used to get above the Earth's obscuring atmosphere. Uncertainties prevailed for a time, and a variety of different theories were advanced to explain the "cosmic radiation." Today, the discrepancies are resolved, and we know that we are "seeing" *blackbody radiation at a temperature of 2.7 degrees Absolute* (that is, 2.7° Centigrade above absolute zero, or -455° Fahrenheit). This is in perfect agreement with the properties expected of the remnant radiation coming to us from the primeval fireball. How awesome it is to realize that we have such a direct view of the beginning of our universe! (See Section IV.)

### E. X-Ray Sources Beyond Our Galaxy

An *X-ray* is electromagnetic radiation with a short wavelength, from $\lambda = 1$ Å to 100 Å. Since there is no "X-ray window" through the Earth's atmosphere, X-ray astronomy could begin only around 1960 when sounding rockets and spacecraft first carried X-ray detectors far above the atmosphere. From the start, our Sun was found to be a bright and complex X-ray source. After 1962, several *point* sources of X-rays, such as Sco X-1 (in the constellation Scorpius) and the Crab Nebula (in Taurus), were discerned in our Galaxy.

It was not until December 1970 that NASA launched the first *X-ray satellite*, UHURU (pronounced "oo-hoo-roo"), for the express purpose of mapping the "X-ray sky." As a result, we presently know of *more than 100* X-ray sources, and many of them are identified with optical objects. Many of these sources reside nearby, in the disk of our Galaxy (see Subsection II.A.), and they are associated with objects such as the hot remnants of exploded stars (supernovae) and the weird "X-ray stars." The remainder are extragalactic.

*Extragalactic X-ray astronomy* is only about *five years old*. Already, NASA satellites have "seen" quasars, active galaxies, clusters of galaxies, and our universe. The observed X-ray sources beyond our Galaxy are of three types:

(1) Strong *point* sources associated with *active* objects, such as quasars (3C 273), Seyfert galaxies (NGC 1275), and radio galaxies (M87).

(2) *Distributed* sources identified with the centers of nearby large *clusters of galaxies*, such as Virgo and Coma. These X-ray-emitting regions are several million light-years in size, and they are generally believed to consist of extremely hot gas (around 10 million degrees). The gas is excited and heated either by a few "violent" galaxies in the clusters or by the rapid orbital motions of all the cluster galaxies (see Subsection III.G.).

(3) The low-intensity *X-ray background* from the universe, which comes toward the Earth uniformly from all directions. (This "cosmic X-radiation" is a complicated subject, and we lack space to discuss it properly here.)

### F. Faster Than the Speed of Light?

During the 1960's, many active extragalactic objects – such as quasars, Seyfert galaxies, and radio galaxies – were found to vary in both optical and radio brightness. These variations correspond to repeated, violent "eruptions" in the nuclei of massive galaxies – in regions about 1 light-year in size. To improve their understanding, extragalactic astronomers wanted to "see" these tiny structures directly, but the task was extremely difficult since 1 light-year at a distance of 1 billion light-years spans an angular diameter of only 0.001 arc-second (the apparent size of an apple 100 000 km away). Optical telescopes were useless, since their best angular resolution is about 1 arc-second. Consequently, astronomers turned to radio astronomy for the solution.

The problem was solved with *very-long-baseline radio interferometry* (VLBI). Radio interferometers (see Subsection III.A.) with huge aperatures were constructed by recording the radio signals at two independent radio telescopes – each with its own atomic clock (stable to one part in a trillion). The two separate records were then synchronized and processed in an electronic computer which became, in effect, an "intercontinental radio interferometer." Beginning in 1967 with an aperture of 10 km (angular resolution of 3 arc-seconds), such VLBI "devices" by the early 1970's had been improved to span the diameter of the Earth giving angular resolutions of 0.0005 arc-second).

With such instruments, extragalactic astronomers verified the the "action" in violent galactic nuclei was indeed occurring in volumes about one light-year in size. But a much more spectacular discovery occurred in early 1971, when the quasar 3C 279 was scrutinized

using VLBI between California and Massachusetts. A *double radio source* only 0.002 arc-second in size was found in the heart of the quasar, and, within 120 days, the two radio components were "seen" to move apart by about 0.00014 arc-second. At the distance implied by the redshift of 3C 279, this observation seemed to imply that *the radio components were separated at 10 times the speed of light*. Since then, other quasars (3C 273), Seyfert galaxies, and radio galaxies have been observed to exhibit similarly "impossible" behavior – nuclear radio sources separating *faster* than twice the speed of light (as "seen" on the plane of the sky) or $2c$. (According to the theory of relativity, material objects cannot move faster than light – speed = $c$ – so two bodies cannot appear to separate faster than $2c$.)

Scientists were able to develop only two simple solutions to the "unthinkable dilemma" caused by these findings. The first was to bring the radio sources much closer to us than the distances indicated by the observed redshifts of the parent objects. However, if implemented, this solution would have reintroduced "intrinsic" redshifts – not only for the quasars (which many people might have accepted), but also for rather "normal" galaxies – and the entire edifice of standard extragalactic astronomy would have crumbled before our eyes! Fortunately, a second easily understood and readily acceptable solution was proposed in the form of the *Christmas Tree Model*. Imagine a galactic nucleus with *several variable* radio sources in it flickering on and off independently like the lights of a Christmas tree. Since VLBI gives us only a "fuzzy" view of the galactic nucleus, we might believe that we were "seeing" a double radio source expanding faster than the speed of light when this "flickering" occurred in the sequence illustrated in figure 8 below. (Sources 1 and 2 are "on" at first, then 2 dims, and 3 comes "on" slowly.) The straightforward model can also accommodate *contracting* and *rotating* "double sources" which seem to move at arbitrary speeds. We presently believe that this theory adequately explains the observations.

Figure 8

### G. Galaxies With "Radio Tails"

Let us end Section III with a radio astronomical "short story," which ties together active (radio) galaxies, large clusters of galaxies, and the gas permeating such clusters. (See Subsection III.E.)

To map out the radio structure of a portion of the sky, we may observe it for several days with a radio interferometer, changing the effective aperture (spacing) each day. This procedure, called *aperture synthesis*, "synthesizes the full dish of a large radio telescope" and can produce the equivalent of a *radio photograph* of the region surveyed.

Using this technique, British radio astronomers in 1968 studied the Perseus cluster of galaxies. They discovered two galaxies – NGC 1265 and IC 310 – with "radio tails" pointing away from the nearby, active Seyfert galaxy, NGC 1275. By 1971, such radio tails had been observed in two other clusters of galaxies. An early explanation of this phenomenon was that the most active galaxy in each cluster was *exciting* the gas in other galaxies to radiate at radio wavelengths and *blowing* this gas out to form the *radio tails*. (An excellent optical analogue is this: Our Sun causes comets to glow and produces their *tails*.)

This theory proved untenable, however, when, in mid-1972, radio astronomers in Holland reobserved the Perseus cluster using aperture synthesis techniques. With greater sensitivity and better angular resolution (30 arc-seconds), they found a galaxy whose radio tail pointed *toward* NGC 1275! In addition, they produced a radio photograph of the radio source 3C 129, showing a galaxy with a helical (corkscrew) radio tail extending a million light-years behind – and the "tail" consisted of *pairs* of radio sources (similar to beads on two strings)!

Today, we believe that the following picture consistently explains all of these results: the interior of a large cluster of galaxies contains much gas and galaxies orbiting around at speeds approaching 1500 km per s. Suppose that one of these galaxies were to develop an active nucleus and "eject" double radio sources. These radio-emitting "clouds" would lag behind the galaxy, since they are slowed by the intracluster gas. A sequence of active phases would result in a radio tail of "glowing" radio sources behind the galaxy, tracing out the galaxy's orbital path through the cluster.

## ADVANCED EXERCISES FOR STUDENTS

**Class Activities:**

1. Most major universities have *radio telescopes* nearby. Take a field trip to a radio telescope installation and view as much of the instrumentation as possible. Talk with the local "radio astronomers" and learn about the output of their observations.

2. If you can, arrange to visit one of the sites of *NASA* – the National Aeronautics and Space Administration. Become familiar with its spacecraft and the types of instruments which are sent above the Earth's atmosphere to detect various forms of electromagnetic radiation. (If this is unfeasible, you can learn of the Administration's activities and

satellites – such as OAO, the Orbiting Astronomical Observatory – by writing for information to: Federal Clearing House for Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151.)

3. Review with your class how the "Christmas Tree Model" of figure 8 works. Then, give students the task of drawing such a "Christmas Tree Model" for each of the following three radio source behaviors: (a) A "double" source "contracts" to half its previous separation. (b) A "double" source "rotates" clockwise through an angle of 30 arc-degrees. (c) A "double" source "expands," then "rotates" through 45 arc-degrees while continuing to expand, and finally rotates 45 arc-degrees more while contracting significantly.

**Questions With Answers:**

**Q1:** Why would radio astronomers be upset if the government permitted commercial "radio" transmissions in the centimeter-wavelength band?

**A1:** Radio telescopes operate at these wavelengths, and they are so fantastically sensitive that such commercial transmissions would overwhelm them.

**Q2:** Name at least three different types of *violent* extragalactic events.

**A2:** Radio galaxies (3C 295), jets from galactic nuclei (M87), exploding galaxies (M82), Seyfert galaxies (NGC 1275), and quasars (3C 273).

**Q3:** If the light emitted by a certain quasar at a given wavelength is *observed to arrive at twice that wavelength*, what is the quasar's *redshift* and how fast is it *receding* from us (on the Doppler interpretation)?

**A3:** Redshift = $z = (2x - x)/x = 1.0$. $v/c = (2 + 1)/(2 + 2 + 1) = 3/5 - 0.6$. The redshift is *one*, and the recession speed is *60* percent of $c$, or 180 000 km per s.

**Q4:** How would you interpret a "radio tail" appearing as two long streams of radio sources, wound around in corkscrew fashion, and gently curving into space?

**A4:** A *rotating* radio galaxy has periodically ejected double radio sources while plowing through the intracluster gas of a cluster of galaxies on a curved trajectory. (Visualize a stunt airplane, emitting synchronized puffs of smoke from its wingtips while performing an arching "barrel roll!")

## IV

## THE "CONVENTIONAL" STORY OF COSMOLOGY

In preceding pages we have related the historical development of extragalactic astronomy, and we have briefly described the important, recent findings of this young science. So that the reader may understand the broad context within which the "pieces" of extragalactic astronomy fit, let us here summarize our discussion in two ways: (1) we place the contents of the universe in their proper locations in space, and (2) we describe the evolution of our universe in time – from its "beginning" to the present day.

Our tiny Earth orbits the nearby Sun, a star typical of the 100 billion stars which comprise our spiral Galaxy. The Andromeda galaxy, about 2 million light-years away, is the nearest large galaxy. This pair of spiral galaxies dominates our Local Group of about two dozen galaxies. The Local Group lies near one edge of the rich Virgo Cluster of galaxies, whose center is 40 million light-years distant (in the constellation Virgo). Space is rather uniformly filled with such clusters of galaxies, out to at least 5 billion light-years – the farthest that ordinary galaxies can be seen with optical telescopes. Approximately 10 billion galaxies are visible to us. And the entire universe of clusters of galaxies is expanding in accordance with Hubble's law.

The basic "building blocks" of the universe are galaxies and clusters thereof. In some nearby clusters, hot gas has been detected at radio and X-ray wavelengths. Galaxies are enormous, and so, tend to change slowly – on time-scales of hundreds of millions of years. But extraordinarily rapid and violent activity is exhibited by the compact nuclei (centers) of many galaxies. Symptoms of this behavior are evident in "exploding" galaxies, Seyfert galaxies, radio galaxies, and the quasars. Quasars are the brightest objects in the universe, and they are visible almost out to the "edge" – about 12 billion light-years distant – where some are seen receding at nearly the speed of light.

Since we view the universe with "light" (electromagnetic radiation), space and time are inextricably linked together by the speed of light. Today, we see the Andromeda galaxy as it was 2 million years ago, for its light takes that long to travel the 2 million light-years separating us. The farther out we peer, the further into the past we are bound to see. A quasar redshifted by $z = 1$ is seen as it was when the light left it 8 billion years ago. The farthest that we can possibly see – the "edge" – corresponds to the beginning of the universe.

By tracing the Hubble expansion of our universe backward in time, we deduce that the universe "began" around 12 billion years ago. The *Big-Bang Theory*, which follows, provides a consistent and believable picture of its subsequent evolution. (It would be too dogmatic to insist that this theory is valid, but it is the best model we have today and is generally accepted by extragalactic astronomers.)

Starting as an incredibly small, dense, and hot primeval fireball of radiation, the universe rapidly expanded and cooled. About half a million years after the beginning, this radiation weakened sufficiently that protons and electrons could bind together to form

neutral hydorgen. This "decoupling" marked the beginning of *galaxy formation*, as the gas began to clump out into dense clouds due to self-gravitation. For about half a billion years, the clouds continued to collapse, and multitudes of stars formed – the galaxies were born! The remnant radiation from the primeval fireball cooled down to become the 2.7-degree-Absolute blackbody radiation which we detect today at cm wavelengths. Soon after large galaxies formed, activity (somehow) ignited in their nuclei; strong quasars and radio sources began to appear. Today, the closest evidence of this cataclysmic violence is provided by the nearby ("feeble") Seyfert galaxies. Time passed, stars died, and new stars formed from the gas and dust in the galaxies.

A critically important event took place in our Galaxy 4.6 billion years ago. The Sun formed, and with it, the Earth. Life arose in the warm waters of the Earth about 3.5 billion years ago, and the steady workings of evolution led inexorably to Man a few million years ago. The recorded history of civilization spans about 5000 years, while science, as we know it, is 400 years old. Extragalactic astronomy appeared on the scene only within the last century, and the story which we have related in this unit was hardly dreamt of at the beginning of the 20th century. Our knowledge of the universe beyond our Galaxy has come within a single lifetime. How fortunate we are to live at this time in history. . .

## FINAL EXERCISES FOR STUDENTS

**Class Activities:**

1. If you are near an *optical telescope observatory*, arrange for your class to visit it one night. View the telescopes and their accessory equipment. Talk with the "astronomers" there. A talk and/or slide show on extragalactic astronomy might also be arranged. (If this is not possible, or in addition, visit your local *planetarium* to view the exhibits and hear a lecture on some aspect of extragalactic astronomy.)

2. Obtain a spherical "weather" balloon (maximum expanded diameter about 2 meters) and paste or paint "dots" on the surface when it is half expanded. The "dots" represent galaxies, so do not crowd them too much. When the "dots" are uniformly scattered on the surface (which represents space), the balloon will represent a model of the universe. Mark long pieces of string, so that they can be used as "flexible meter sticks" on the balloon's surface. Distinguish one "dot" as our Galaxy (paint it red?). When the balloon is small, have the students measure (and record) the "distance" from our Galaxy to several (all?) other "galaxies." Then, expand the balloon significantly and repeat the experiment. The students should then compute the increase in distances to each "galaxy" caused by the expansion and plot each result versus the average distance on a linear graph. A straight line – Hubble's law – should result. (Some students might also measure *all* of the "distances" between *all* of the "galaxies" each time in order to prove that all "dots" recede from each other when the balloon expands.)

**Questions with Answers:**

**Q1:** Knowing that Hubble's constant is $H = 20$ (km per s) per (million light-years), what is the value of $T = 1/H$ in years?

**A1:** $T = 1/20$ (km per s) per (million light-years)
= (300 000 km per s) x (1 million light-years)/20 km per s
= 15 000 000 000 years = 15 billion years.
Hence, $T$ (the "Hubble time") is approximately the *age* of our universe!

**Q2:** If we model the distance to the Andromeda galaxy as one m, how far from our Galaxy would we find (a) the quasar 3C 273, (b) the most distant galaxy known (3C 295, with $z = 0.46$), and (c) the "edge" of the Universe?

**A2:** (a) 1 km, (b) about 2.5 km, and (c) about 7 km.

**Q3:** If the "visible edge" of the universe corresponds to its beginning, what would you expect to "see" *beyond* the "edge"?

**A3:** Those events *preceding* the beginning of the universe, if there were any!

**Q4:** Using Hubble's law, $v = Hd$, calculate the general distance to the "edge" of the universe.

**A4:** Nothing travels faster than light, so let us set $v = c$. Then we find: $d = c/H = c \times (1/H)$ $= cT = 15$ billion light-years, from Problem 1 above.

## GLOSSARY

Ångström Unit– a small unit of length equal to 1/100 000 000 or $10^{-8}$ cm, used to measure wavelengths of optical light and X-rays.

angular resolution– the smallest angle on the sky that can be discerned as a structured by a detector of electromagnetic radiation.

aperture– the diameter of the collecting surface of a telescope.

aperture synthesis– the use of variable-aperture radio interferometer to mimick the "full dish" of a huge equivalent radio telescope.

arc-degree– a unit of angle equal to 1/360th of a complete circle.

arc-minute– a unit of angle equal to 1/21 600th of a complete circle (also 1/60th arc-degree).

arc-second– a unit of angle equal to 1/60th arc-minute.

big-bang– the "explosion" which began our universe; also, the name of the standard theory of the evolution of our expanding universe.

blackbody– a perfect, thermal ("hot") radiator of electromagnetic radiation.

blueshift– when a given emitted wavelength of radiation is observed as a shorter wavelength; generally caused by relative motion of source and observer.

centi– a prefix meaning *one hundredth*; 1 cm equals 1/100th m.

Cepheid variable– a giant star which pulsates periodically in brightness.

Christmas tree model– the theory of nuclear radio sources whereby independent variable sources produce "apparent motions" in active galactic nuclei.

cluster of galaxies– two to 10 000 galaxies physically grouped in space.

color– the human eye's response to different wavelengths of visible light.

comet– a dirty-ice "rock" orbiting in the solar system which the Sun causes to vaporize, glow visibly, and stream out a long, luminous tail.

constellation– the easily identifiable configuration of the brightest visible stars in a moderately small region of the night sky.

cosmological interpretation– the viewpoint that a redshift implies a distance according to Hubble's law; the redshift is not "intrinsic" to the source.

cosmology– the study of the content, structure, and evolution of the universe.

degree absolute– a "Centigrade" temperature scale beginning at absolute zero; water freezes at 273 degrees Absolute and boils at 373 degrees Absolute.

Doppler effect– whereby radiation of a given emitted wavelength is caused to be observed at a different wavelength due to the relative motion of the source and the observer along the line joining them.

electromagnetic radiation– a mutual disturbance of electric and magnetic fields which travels through a vacuum at the speed of light.

extragalactic– farther than 100 000 light-years; beyond our galaxy.

extraterrestrial– beyond the top of the Earth's atmosphere.

galaxy– a stellar system of from 1 000 000 to 1 000 000 000 000 stars; our own such system is capitalized (Galaxy) and all others are lower-case (galaxy).

gamma ray– energetic electromagnetic radiation of very short wavelength (less than 1 Ångström).

globular cluster– a compact cluster of about one million stars orbiting a galaxy.

Hubble's law– the statement that the redshifts of extragalactic objects are *directly proportional* to their distances from us.

infrared– optical electromagnetic radiation in the wavelength range from 7000 Å to 0.01 cm; we call part of this range "heat."

lenticular– refers to the 50 galaxies, which look like a "lens" seen edge-on.

light– the common term for visible electromagnetic radiation.

light-month– the distance light travels in one month; 1 000 000 000 000 km.

light-year– the distance light travels in one Earth-year (abbreviated 1 yr); approximately 10 000 000 000 000 km.

local group– the small grouping of about 20 galaxies, of which our Galaxy and the Andromeda galaxy are the dominant members.

Magellanic clouds– the two dwarf galaxies closest to our Galaxy (170 000 light-years); easily visible to the naked eye from the southern hemisphere.

microwave– an alternate term for radio waves of cm wavelength.

Milky Way– a diffuse band of light circling the heavens; the plane of our Galaxy as seen from Earth; another name for our Galaxy.

nebula– Latin for "cloud" (plural is nebulae); any of the thousands of diffuse patches of light seen telescopically on the night sky; a luminous cloud of gas or dust in our Galaxy; a galaxy before about 1925 A.D.

nova– Latin for "new" (plural is novae); usually applied to a star which "explodes" and suddenly becomes readily visible in the night sky.

nucleus– the very compact center of a galaxy, where "activity" can occur.

optical telescope– a device for collecting and focusing optical light, using glass lenses and/or curved mirrors.

primeval fireball– the holocaust of radiation dominating the early stages of the expansion of our universe; seen today as "cosmic microwave radiation".

quasar– a star-like optical object (in appearance), whose light is very highly redshifted; believed to be a super-violent galactic nucleus.

quasi-stellar– literally, "appearing star-like"; another name for quasar.

radio– weak electromagnetic radiation with long wavelengths (greater than 0.01 cm).

radio galaxy– an optical galaxy (usually elliptical) producing strong radio sources in its vicinity.

radio interferometer– two or more individual radio telescopes joined electrically to mimick the angular resolution of a larger "radio telescope."

radio source– a localized region of the sky from which radio waves are detected.

radio tail– the long "tail-like" radio source trailing some radio galaxies.

radio telescope– a large, metallic device which collects and focuses radio waves onto a sensitive radio receiver; the "dish" is usually "steerable."

redshift– when a given, emitted wavelength of radiation is observed as a longer wavelength.

redshift controversy– the recent debate concerning the interpretation of the meaning of extragalactic redshifts; whether redshifts indicate cosmological distances via Hubble's law or are "intrinsic" to their sources.

relativistic– moving at speeds approaching the speed of light.

Seyfert galaxy– a "spiral" galaxy whose nucleus is active, star-like, and very bright, and from which spectroscopy indicates rapid gas outflow.

speed of light– the propagation speed of electromagnetic radiation in a vacuum; $c =$ 300 000 km per s.

spectroscopy– the physical science whereby the "*colors*" of light are separated, their relative intensities measured, and the result interpreted in terms of the physical properties of the sources of light.

standard-candle– denoting a class of objects, all with the same intrinsic brightness.

star– a massive "ball" of hot, luminous gas; similar to our Sun.

supercluster– a larger grouping of clusters of galaxies.

supernova– the brightest and most violent exploding stars (plural is supernovae).

synchrotron radiation– the electromagnetic radiation emitted by relativistic charged particles (usually electrons) spiraling in a magnetic field.

ultraviolet– moderately energetic electromagnetic radiation with wavelengths from 100 Å to 4000 Å.

universe– everything that was, is, or will be in space and time.

VLBI– means "very-long-baseline radio interferometry"; when an enormous radio interferometer is created by separately recording radio waves at two radio telescopes and bringing the records together at a computer for analysis.

wavelength– the distance between successive crests or valleys of a travelling wave phenomenon.

window– those wavelength bands at which the Earth's atmosphere is essentially transparent to electromagnetic radiation – optical and radio.

X-ray– energetic electromagnetic radiation with wavelengths from 1 Å to 100 Å.

X-ray source– a localized region of the sky from which X-rays are detected.

zone of avoidance– essentially the band of the Milky Way on the sky; where our Galaxy obscures extragalactic objects due to the gas and dust in its plane.

## REFERENCES AND TEACHING AIDS

### PERIODICALS:

*American Scientist* (bimonthly), Society of the Sigma Xi, New Haven, Connecticut.

*Astronomy* (monthly), Astromedia Corporation, 757 North Broadway, Suite 204, Milwaukee, Wisconsin 53202.

*Physics Today* (monthly), The American Institute of Physics, New York, New York.

*Publications of the Astronomical Society of the Pacific* (bimonthly), California Academy of Sciences, San Francisco, California 94118.

*Scientific American* (monthly), W. H. Freeman and Company, 660 Market Street, San Francisco, California 94104.

*Sky and Telescope* (monthly), Sky Publishing Corporation, 50 Bay Street, Cambridge, Massachusetts 02138.

*Griffith Observer* (monthly), Griffith Observatory, P.O. Box 27787, Los Angeles, California 90027.

### JOURNAL ARTICLES:

Burbidge, G. R., *et al.*, "Evidence for the Occurrence of Violent Events in the Nuclei of Galaxies", *Reviews of Modern Physics*, Vol. 35, No. 4, pp. 947-972, October 1963.

Chiu, Hong-Yee, "The Evolution of the Universe", *Science Journal*, Vol. 4, No. 8, pp. 33-38, August 1968.

Colgate, Stirling A., "Quasistellar Objects and Seyfert Galaxies", *Physics Today*, Vol. 22, pp. 27-35, January 1969.

Fernie, J. D., "The Period-Luminosity Relation: A Historical Review", *Publications of the Astronomical Society of the Pacific*, Vol. 81, pp. 707-731, December 1969.

Hjellming, Robert M., "Radio Astronomy", *McGraw-Hill Yearbook of Science and Technology*, pp. 1-11, 1974.

Miley, G. K., *et al.*, "Active Galaxies with Radio Tails in Clusters", *Nature*, Vol. 237, pp. 269-272, June, 2, 1972.

Partride, R. B., "The Primeval Fireball Today", *American Scientist*, Vol. 57, pp. 37-74, 1969.

Sandage, Allan R., "Cosmology: A Search for Two Numbers", *Physics Today*, Vol. 23, No. 2, pp. 34-41, February 1970.

Van den Bergh, Sidney, "Extragalactic Distance Scale", *Nature*, Vol. 225, pp. 503-505, February 7, 1970.

Weaver, Kenneth F., "The Incredible Universe", *National Geographic*, Vol. 145, No. 5, pp. 589-625, May 1974.

Webster, Adrian, "The Cosmic Background Radiation", *Scientific American*, Vol. 231, No. 2, pp. 26-33, August 1974.

**TEXTBOOKS:**

Abell, George, *Exploration of the Universe*. Holt, Rinehart and Winston (second edition), New York, 1969.

Bonner, William B., *The Mystery of the Expanding Universe*. The Macmillan Company, New York, New York, 1964.

Brandt, John C., and Stephen P. Maran, *New Horizons in Astronomy*. W. H. Freeman and Company, San Francisco, California, 1972.

Gamow, George, *The Creation of the Universe*. Bantam Books, 1960.

Jastrow, Robert, and Malcolm H. Thompson, *Astronomy: Fundamentals and Frontiers*. John Wiley & Sons, New York, New York, 1972.

Kaufmann, William Jr., *Relativity and Cosmology*. Harper & Row, New York, New York, 1973.

North, J. D., *The Measure of the Universe*. The Clarendon Press, Oxford, 1965.

Sciama, Dennis W., *Modern Cosmology*. Cambridge University Press, Cambridge, 1971.

Smith, Elske V. P., and Kenneth C. Jacobs, *Introductory Astronomy and Astrophysics*. W. B. Saunders Company, Philadelphia, Pennsylvania, 1973.

Verschuur, G. L., *The Invisible Universe*. Springer-Verlag, New York, New York, 1974.

Wyatt, Stanley P., *Principles of Astronomy*. Allyn and Bacon (second edition), Boston, Massachusetts, 1971.

**OTHER LITERATURE:**

Berendzen, R., and D. DeVorkin, "Resource Letter EMAA-1: Educational Materials in Astronomy and Astrophysics", *American Journal of Physics*, Vol. 41, pp. 783-808, 1973. Reprints available at 50 cents each from Arnold A. Strassenburg, Executive Officer, American Association of Physics Teachers, Drawer AW, Stony Brook, New York 11790.

Calder, Nigel, *Violent Universe* (An Eyewitness Account of the New Astronomy). The Viking Press, New York, New York, 1970.

Field, George B., *et al.* (editors), *The Redshift Controversy*. W. A. Benjamin, Inc., Reading, Massachusetts, 1973.

Gingerich, Owen (editor), *Frontiers in Astronomy* (readings from Scientific American). W. H. Freeman and Company, San Francisco, California, 1970.

Hodge, Paul W., *Galaxies and Cosmology*. McGraw-Hill Book Co., New York, New York, 1966.

Hodge, Paul W., *Concepts of the Universe*. McGraw-Hill Book Co., New York, New York, 1969.

Jones, Kenneth Glyn, *Messier's Nebulae and Star Clusters*. American Elsevier Publishing Company, New York, New York, 1969.

Munitz, Milton K. (editor), *Theories of the Univers*. The Free Press, New York, New York, 1965.

Sandage, Allan, *The Hubble Atlas of Galaxies*. Carnegie Institution of Washington, Publication No. 618, Washington, D.C., 1961.

Saslaw, William C., and Kenneth C. Jacobs, *The Emerging Universe* (essays on Contemporary Astronomy). The University Press of Virginia, Charlottesville, Virginia, 1972.

Struve, Otto, and Velta Zebergs, *Astronomy of the Twentieth Century*. The Macmillan Company, New York, New York, 1962.

Whitney, Charles A., *The Discovery of our Galaxy*. Angus & Robertson, Ltd., London, 1971.

**PHOTOGRAPHS (EXTRAGALACTIC):**

Astro-Murals, Box 7563-T, Washington, D.C. 20044.

Hale Observatories: series in color and black-and-white. Order catalogue from California Institute of Technology Bookstore, 1201 E. California Blvd., Pasadena, California 91109. Order photographs from Hansen Planetarium, 15 South State St., Salt Lake City, Utah 84111.

Lick Observatory: series in color and black-and-white. Lick Observatory, University of California, Santa Cruz, California 95060.

Yerkes Observatory, Williams Bay, Wisconsin 53191.

**SLIDES (EXTRAGALACTIC):**

Astro-Murals, Box 7563-T, Washington, D.C. 20044.

Hale Observatories: about 100 35mm slides. Order from California Institute of Technology Bookstore, 1201 E. California Blvd., Pasadena, California 91109.

Hodge, Paul, *Hodge Slide Set for Astronomy and Study Guide*. McGraw-Hill Book Company, New York, New York, 1973. A total of 250 35mm slides in color and black-and-white; see especially Set No. 51 on "Galaxies and the Universe".

Lick Observatory, University of California, Santa Cruz, California 95060. Slides (2″x2″) in color and black-and-white; see especially the series A, G, N, MW and/or S slides.

Norton Scientific: 35mm slides; see especially Series F, G, I, J, K and/or Q. Order from Norton Scientific, P.O. Box 9212, Reno, Nevada 89507.

Tersch Enterprises: 35mm slides; see especially sets number 33, 7, 8, 9, and 108 (in color) and 5, 17, 20, 59, 60, 77, and 79 (in black-and-white). Order from Tersch Enterprises, P.O. Box 1059, Colorado Springs, Colorado 80901.

Yerkes Observatory, Williams Bay, Wisconsin 53191.

**FILMS:**

*Radio Sky*, 1966 (28 min., color). $100 to purchase from Associated Electrical Industries, 33 Grosvenor Place, London S.W.1, England.

*Radio View of the Universe*, 1967 (28.5 min., color, narrated by M. S. Roberts). Rental $3 from Astronomical Society of the Pacific, c/o G. Perkins, 4636 Vineta Avenue, La Canada, California 91011.

*The Universe from Palomar* (40 min., 16mm color film with sound). Rental $20 per day or $200 to buy from Audio-Visual Services, California Institute of Technology, Pasadena, California 91109.

*Violent Universe*, 1969 (148 min., five reels of black-and-white, narrated by Nigel Calder). Rental is $28 from Extension Media Center, University of California, Berkeley, California 94720.

*Powers of Ten*, 1968 (8 min., 16mm color film with sound). Rent $10 from University of Southern California, Division of Cinema, University Park, Los Angeles, California 90007 (Attention: Film Distribution Section).

*To the Edge of the Universe*, 1971 (23 min., color, code number 101789-5). Rental is $15 from McGraw-Hill Text Films, 1221 Avenue of the Americas, New York, New York.

NASA films. For information write to NASA Headquarters, Code FAD, Washington, D.C. 20546.

Time-Life films. For information write to Time-Life Films, Inc., Time & Life Building, New York, New York 10020.

*Galaxies and the Universe*, 1969 (13.5 min., color, code number 130-3317). Rental $8 from Modern Film Rentals, 2323 New Hyde Park Road, New Hyde Park, New York 11040.

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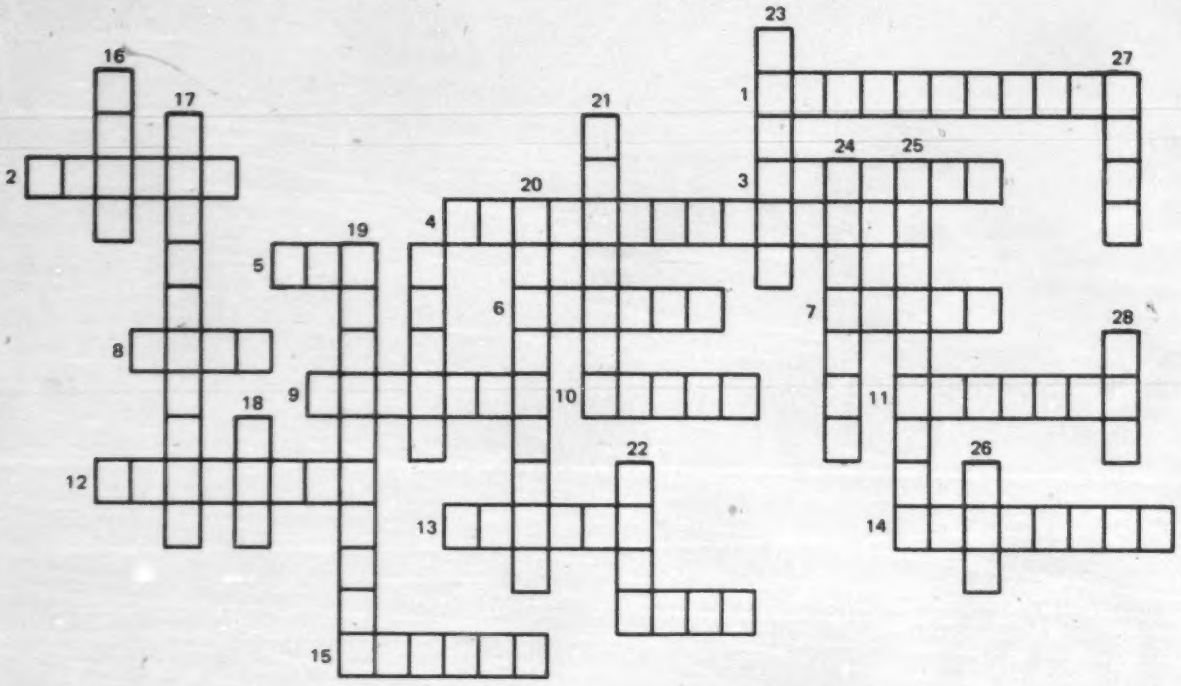

**ACROSS:**

1. Radiation with wavelengths just shorter than those of visible light.
2. Our Galaxy is thought to be a _____ galaxy.
3. The generally accepted theory of our expanding universe.
4. A radio galaxy is optically an_____(oval) galaxy.
5. The universe of galaxies expands in accordance with Hubble's _____.
6. Our Sun resides in the Milky Way_____.
7. The nearest large cluster of galaxies is in the constellation _____.
8. Abbreviation for "intercontinental" radio interferometry.
9. A_____ galaxy has a bright, star-like, active nucleus.
10. The "window" opened by Jansky in 1931-2.
11. M101 is one of the_____ objects.
12. Everything in space and time.
13. Common name for QSRS or QSO.
14. Unit of length for describing light waves and atoms.
15. He showed the "nebulae" to be galaxies in extragalactic space.

**DOWN:**

16. In some clusters a radio galaxy is followed by a radio_____.
17. The nearest galaxies in the Local Group are the_____ Clouds.
18. From M87 and 3C 273 there emerges a strange optical_____.
19. The distance between adjacent "crests" of a travelling wave.
20. A light ray goes this far in vacuum in one Earth-year.
21. Due to relative motion, the_____ Effect changes wavelengths of light.
22. The UHURU satellite found many_____ sources.
23. He discovered the expansion of our universe.
24. A galaxy is held together by the_____ of its stars.
25. M31 is commonly known as the_____ galaxy.
26. Abbreviation for galaxies in the New General Catalogue.
27. The Christmas_____ Model accounts for "faster than light" radio sources.
28 The standard abbreviation for an irregular galaxy, like M82

(4.) The light from quasars suffers a large red_____.